

Effect of density on quantum Hall stripe orientation in tilted magnetic fields

Q. Shi,¹ M. A. Zudov,¹ Q. Qian,² J. D. Watson*,² and M. J. Manfra^{2,3,4}

¹*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*

²*Department of Physics and Astronomy and Birck Nanotechnology Center,
Purdue University, West Lafayette, Indiana 47907, USA*

³*Station Q Purdue, Purdue University, West Lafayette, Indiana 47907, USA*

⁴*School of Materials Engineering and School of Electrical and Computer Engineering,
Purdue University, West Lafayette, Indiana 47907, USA*

(Received April 12, 2017)

We investigate quantum Hall stripes under in-plane magnetic field B_{\parallel} in a variable-density two-dimensional electron gas. At filling factor $\nu = 9/2$, we observe one, two, and zero B_{\parallel} -induced reorientations at low, intermediate, and high densities, respectively. The appearance of these distinct regimes is due to a strong density dependence of the B_{\parallel} -induced orienting mechanism which triggers the second reorientation, rendering stripes *parallel* to B_{\parallel} . In contrast, the mechanism which reorients stripes perpendicular to B_{\parallel} showed no noticeable dependence on density. Measurements at $\nu = 9/2$ and $11/2$ at the same, tilted magnetic field, allows us to rule out density dependence of the native symmetry-breaking field as a dominant factor. Our findings further suggest that screening might play an important role in determining stripe orientation, providing guidance in developing theories aimed at identifying and describing native and B_{\parallel} -induced symmetry-breaking fields.

Quantum Hall stripe phases [1–21] represent one class of exotic states that appear in a two-dimensional electron gas (2DEG) subjected to perpendicular magnetic fields and low temperatures. These phases manifest charge clustering originating from a box-like interaction potential [1, 2] owing to ring-shaped wavefunctions in higher Landau levels (LLs). A built-in symmetry-breaking potential in the GaAs quantum well, hosting a two-dimensional electron gas (2DEG), macroscopically orients stripes along $\langle 110 \rangle$ crystal direction, with very few exceptions [8, 15, 20]. Despite continuing efforts [13, 14, 20, 22], the origin of such preferred native orientation remains a mystery. It is known, however, that due to a finite thickness of the 2DEG, an in-plane magnetic field B_{\parallel} modifies both the wavefunction and interactions which, in turn, can change stripe orientation [23, 24].

While early experiments [5–7] and theories [23, 24] consistently showed that B_{\parallel} favors stripes perpendicular to it [25], subsequent studies revealed limitations of this “standard picture”. For example, in a tunable-density heterostructure insulated gate field effect transistor [8] native stripes along $\langle 110 \rangle$ crystal direction did not reorient by B_{\parallel} . In other experiments, however, reorientation occurred even when B_{\parallel} was applied perpendicular to the native stripes [11, 19, 26]. Finally, it was recently reported that B_{\parallel} applied along native stripes can induce two successive reorientations, first perpendicular and then parallel to B_{\parallel} [19].

Together, these experiments indicate that the impact of B_{\parallel} on stripe orientation remains poorly understood and is far more complex than suggested by a “standard picture” [23, 24]. In particular, all examples mentioned above revealed that B_{\parallel} can, in fact, favor *parallel* (to B_{\parallel}) stripe alignment. It was also found that the B_{\parallel} -induced mechanism which favors such alignment is highly

sensitive to both spin and orbital quantum numbers [19]. To shed light onto the nature of this mechanism, it is very desirable to identify a tuning parameter that would enable one to control stripe orientation under B_{\parallel} .

In this Rapid Communication we study the effect of the carrier density n_e on stripe orientation in a single-subband 2DEG under B_{\parallel} applied along native stripes ($\parallel \langle 110 \rangle$). At filling factor $\nu = 9/2$, we demonstrate three distinct classes of behavior. At low n_e , we observe a single reorientation (at $B_{\parallel} = B_1$) which renders stripes perpendicular to B_{\parallel} , in agreement with the “standard picture” [5, 6, 23, 24]. At intermediate n_e , we also detect the second reorientation (at $B_{\parallel} = B_2$) which reverts stripes back to their native direction, parallel to B_{\parallel} . Finally, at higher n_e we find that B_{\parallel} cannot alter stripe orientation. We further construct a phase diagram of the stripe orientation which reveals that B_1 is independent of n_e , whereas B_2 decreases rapidly with n_e and eventually merges with B_1 . The appearance of the robust regime of stripes parallel to B_{\parallel} at higher n_e can be attributed to a reduced screening due to increased inter-LL spacing. At the same time, a density sweep at $\nu = 9/2$ and $\nu = 11/2$ at a fixed tilted magnetic field suggests that any density dependence of the native symmetry-breaking field is not an important factor in determining stripe orientation. These findings can provide guidance to future theoretical proposals aimed at explaining parallel stripe alignment with respect to B_{\parallel} and identifying the native symmetry-breaking field.

Our 2DEG resides in a 30-nm GaAs/AlGaAs quantum well (about 200 nm below the sample surface) that is doped in a 2 nm GaAs quantum well at a setback of 63 nm. The *in situ* gate consists of an n^+ GaAs layer situated 850 nm below the bottom of the quantum well [27]. Eight Ohmic contacts were fabricated at the corners

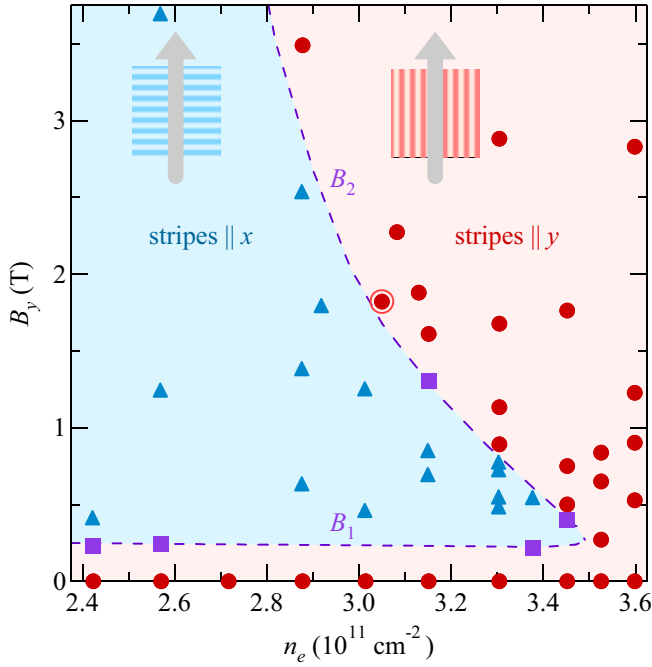


FIG. 1. (Color online) Stripe orientation as a function of n_e and B_y at $\nu = 9/2$. Triangles (circles) mark stripe orientation perpendicular (parallel) to $B_{\parallel} = B_y$. The big circle was obtained from the density sweep in Fig. 2. Squares mark the isotropic state. The lower (upper) phase boundary (dashed line) is a guide to the eyes marking $B_{\parallel} = B_1$ ($B_{\parallel} = B_2$), see the text.

and midsides of the lithographically-defined $1 \times 1 \text{ mm}^2$ Van der Pauw mesa. The electron density n_e was varied continuously from 2.2 to $3.8 \times 10^{11} \text{ cm}^{-2}$. The peak mobility was about $\mu \approx 1.2 \times 10^7 \text{ cm}^2/\text{Vs}$ at $n_e \approx 3.3 \times 10^{11} \text{ cm}^{-2}$. Resistances R_{xx} ($\hat{x} \equiv \langle 1\bar{1}0 \rangle$) and R_{yy} ($\hat{y} \equiv \langle 110 \rangle$) were measured by a standard low-frequency lock-in technique at temperature of about 0.1 K to avoid possible metastable orientations [8, 9]. An in-plane magnetic field $B_{\parallel} \equiv B_y$ was introduced by tilting the sample.

In Fig. 1 we summarize our experimental findings at $\nu = 9/2$, namely the phase diagram of stripe orientation in the (n_e, B_y) -plane. The diagram contains two distinct phases, “stripes $\parallel \hat{x}$ ” and “stripes $\parallel \hat{y}$ ”. While the native stripes are along the \hat{y} -axis at all densities studied, one easily identifies three distinct evolutions of stripe orientation with B_{\parallel} . At low densities we observe a *single* reorientation ($\hat{y} \rightarrow \hat{x}$), in accord with the “standard picture” [5–7, 23, 24, 28]. At intermediate densities, the stripes undergo *two* successive reorientations ($\hat{y} \rightarrow \hat{x}$ and $\hat{x} \rightarrow \hat{y}$), ultimately aligning along B_{\parallel} [19]. Finally, the high density regime reveals *no* reorientations whatsoever, and the native direction of the stripes ($\parallel y$) is preserved at all B_{\parallel} . While each of these regimes was previously realized in individual samples [5, 6, 8, 11, 19], to our knowledge, it is the first observation of all three classes of behavior in a single device.

Further examination of the phase diagram (Fig. 1)

shows that the characteristic in-plane field $B_y = B_1$, describing the first ($\hat{y} \rightarrow \hat{x}$) reorientation, is virtually independent of n_e , as revealed by essentially horizontal lower boundary at $B_1 \approx 0.25 \text{ T}$ of the “stripes $\parallel \hat{x}$ ” phase. On the other hand, the in-plane field $B_y = B_2$, corresponding to the second ($\hat{x} \rightarrow \hat{y}$) reorientation (the upper boundary of the “stripes $\parallel \hat{x}$ ” phase) decreases sharply with n_e until it merges with B_1 at $n_e \approx 3.5 \times 10^{11} \text{ cm}^{-2}$. Indeed, B_2 drops by an order of magnitude over a density variation of less than 20 %. It is this steep dependence of B_2 on n_e that is responsible for the appearance of the three distinct regimes discussed above.

As pointed out in Ref. 19, which investigated both B_1 and B_2 at fixed n_e , B_2 depends strongly on spin and orbital indices, in sharp contrast to B_1 ; at $\nu = 11/2$, B_2 is significantly higher than at $\nu = 9/2$. This observation, together with theoretical considerations [23] predicting similar B_{\parallel} -induced anisotropy energies favoring perpendicular stripes at these filling factors, has lead to the conclusion that the second reorientation is of a different origin [19]. The observation of strong (weak) n_e -dependence of B_2 (B_1) lends further support to this notion.

The B_{\parallel} -induced anisotropy energy E_A evaluated at $B_{\parallel} = B_1$ is routinely used as a measure of the native anisotropy energy $E_N > 0$, which aligns stripes along the $\langle 110 \rangle$ direction at $B_{\parallel} = 0$. More specifically, the positive (negative) sign of the total anisotropy energy $E = E_N - E_A$ [29] is reflected in the parallel (perpendicular) stripe alignment with respect to B_{\parallel} . Within this picture, n_e -independent B_1 suggests that E is not affected by n_e at $B_{\parallel} \approx B_1$. However, E_A depends on the perpendicular magnetic field B_z and on the separation between subbands Δ , both of which change appreciably [30] within the density range of Fig. 1. While the exact effect of n_e on E_N is not known, two experiments [8, 9] revealed that E_N vanishes and becomes negative above a certain n_e . In light of all these effects it is indeed surprising that B_1 [defined by $E_N(n_e) = E_A(B_1, n_e)$] does not depend on n_e reflecting either that none of these effects is significant or that the respective changes in E_A and E_N compensate each other.

The rest of the phase diagram in Fig. 1 clearly shows that stripe orientation is determined not by B_{\parallel} alone, but also by n_e . In particular, the rapid decay of B_2 and its merger with B_1 indicate that at higher n_e (and higher B_{\parallel}) stripes are more likely to be oriented parallel to B_{\parallel} . The decrease of B_2 with n_e , in principle, can be due to either increasing E_N [8, 9] and/or decreasing E_A . However, in the regime of large $B_{\parallel} \gg B_1$, any change of E_N is unlikely to play a big role and, as we show below, it is indeed not the driving force for the n_e -induced stripe reorientation observed at $B_{\parallel} > B_1$ in Fig. 1.

As discussed above, E_A is governed by B_z and by the inter-subband splitting Δ , both of which vary with n_e at fixed $\nu = 9/2$, complicating the interpretation of Fig. 1.

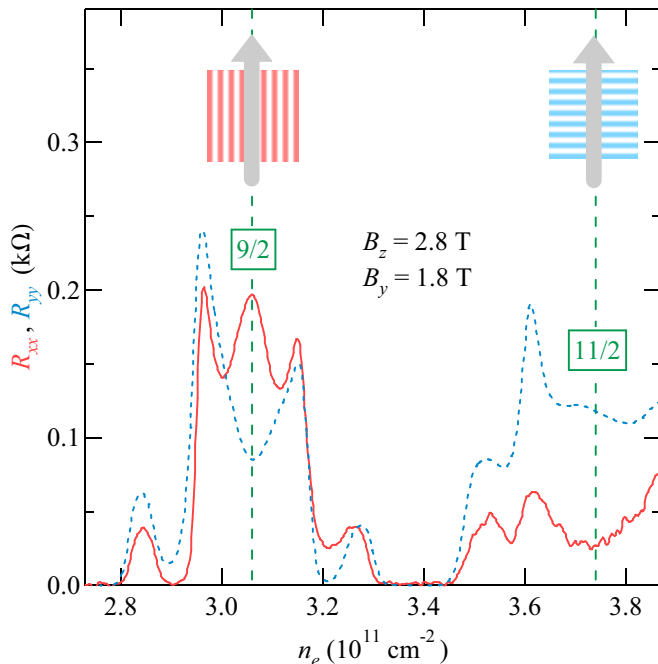


FIG. 2. (Color online) R_{xx} and R_{yy} vs. n_e measured at $B_z = 2.8$ T and $B_y = 1.8$ T.

Additional information can be obtained if one fixes B_z and $B_{||}$ and compares $\nu = 9/2$ and $11/2$ while varying n_e [31]. To this end we have measured R_{xx} and R_{yy} at a fixed $B_z = 2.8$ T and $B_y = 1.8$ T while sweeping the gate voltage to cover these filling factors. In Fig. 2 we present R_{xx} (solid line) and R_{yy} (dotted line) as a function of n_e . At $\nu = 9/2$, which occurs at a lower n_e , $R_{xx} > R_{yy}$ and stripes are parallel to \hat{y} , as a result of the second reorientation which has just occurred (cf. open circle in Fig. 1). In contrast, at $\nu = 11/2$, which is at a higher n_e , we find $R_{xx} < R_{yy}$ implying that stripes are still perpendicular to $B_{||}$. This finding might appear puzzling as it indicates that the overall trend in Fig. 1, namely that higher n_e favors stripes parallel to $B_{||}$, is completely reversed by simply changing the spin index.

Before discussing E_A , we first examine if any possible density dependence of E_N can explain opposite reorientation behaviors in Fig. 1 and Fig. 2. Increasing gate voltage (at either fixed ν or fixed B_z) modifies quantum confinement which can affect E_N , e.g. by changing the spin-orbit coupling [22] and the strength of the interface potential experienced by electrons [8]. However, since all the effects associated with quantum confinement are included Fig. 1 and Fig. 2 on an equal footing and they cannot be the reason for the contrasting behaviors [32].

Having concluded that the change of E_N is of minor importance, we can now focus on E_A alone. Since the effects associated with the change of B_z are absent in Fig. 2, but present in Fig. 1, it follows that they should play a dominant role in triggering n_e -induced parallel stripe alignment observed at $B_{||} = B_2$ in Fig. 1. One

such effect is screening from other LLs which gets weaker with B_z due to increased inter-LL spacing. While theory always yields $E_A > 0$ in a single-subband 2DEG when screening is taken into account, it does produce $E_A < 0$ when screening is neglected [23]. One can therefore expect stripes parallel to $B_{||}$ if screening in realistic samples is weaker than calculations suggest [33–35]. While there are other B_z -related effects that might affect E_A , ($\hat{x} \rightarrow \hat{y}$) stripe reorientation with increasing n_e in Fig. 1 can be explained qualitatively by decreasing screening which favors stripes parallel to $B_{||}$.

On the other hand, what exactly drives the reorientation in Fig. 2 is not clear. Since E_A relies on the finite thickness of the 2DEG, the initial decrease of Δ enhances E_A [23, 24], in agreement with recent measurements of B_1 [20]. However, when the valence LL is sufficiently close to the second subband (i.e., when $\hbar\omega_c/\Delta$ is slightly below 0.5 at $\nu = 9/2$ or $11/2$), the system becomes more akin to a two-subband system resulting in a lower E_A [7, 23, 36]. The n_e -driven ($\hat{y} \rightarrow \hat{x}$) reorientation of stripes in Fig. 2 implies that E increases with decreasing Δ . However, judging what happens to E_A based on theoretical calculations [23] is not possible because a decrease of E_A with $B_{||}$, observed at both $\nu = 9/2$ and $11/2$ under the conditions of Fig. 2, is not anticipated in a single-subband system [23]. In addition, as discussed above, E_N might also change in the density sweep.

It remains to be understood why stripes parallel to $B_{||}$ in a single-subband quantum well are never predicted by theories [23] that calculate the dielectric function using the random phase approximation (RPA) [33]. While we cannot point out the exact reason, it appears plausible that such calculations might not accurately capture a real experimental situation. For example, the period of the stripe phase might be different from what Hartree-Fock calculations suggest. Experiments employing surface acoustic waves have obtained about a 30% larger stripe period than suggested by theory [1, 2]. In addition, LL mixing effects beyond the RPA or disorder-induced LL broadening [22] were not taken into account.

While the phase diagram of stripe orientation shown in Fig. 1 clearly identifies a robust regime of stripes parallel to $B_{||}$, it would indeed be interesting to extend studies to even higher carrier densities without populating the second subband. In particular, it might allow observation of all three distinct regimes at other filling factors, e.g. $\nu = 11/2, 13/2, 15/2$. In addition, higher n_e might reveal a regime of native stripe orientation along the $\langle 110 \rangle$ crystal direction which might allow us to establish a connection, if any, with the findings of Ref. 8.

In summary, we have studied the effect of the carrier density n_e on stripe orientation in a single-subband 30 nm-wide GaAs quantum well under $B_{||}$ applied along native stripes ($\parallel \langle 110 \rangle$). At filling factor $\nu = 9/2$, we have observed one, two, and zero $B_{||}$ -induced stripe reorientations at low, intermediate, and high density, respectively.

The in-plane magnetic field $B_{\parallel} = B_1$, which reorients stripes perpendicular to it in accord with the “standard picture” [5, 6, 23, 24], changes only slightly, if at all, over a wide range of densities. In contrast, the second characteristic field $B_{\parallel} = B_2$, which renders stripes parallel to B_{\parallel} , rapidly decays with density eventually merging with B_1 . The observation that increasing carrier density promotes stripes parallel to B_{\parallel} can be qualitatively ascribed to a weaker screening due to increased inter-LL spacing which can reduce B_{\parallel} -induced anisotropy energy and even change its sign [23]. At the same time, our data suggest that the density dependence of the native symmetry-breaking field, if any, is not an important factor in determining stripe orientation. Our findings provide guidance to future theories attempting to explain parallel stripe alignment with respect to B_{\parallel} and to identify the native symmetry-breaking field. These theories should also take into account experimental evidence [8, 11, 19] for anisotropic nature of E_A .

We thank I. Dmitriev, A. Kamenev, B. Shklovskii, and I. Sodemann for discussions and H. Baek, G. Jones, S. Hannas, T. Murphy, and J. Park for technical assistance. The work at Minnesota (Purdue) was supported by the U.S. Department of Energy, Office of Science, Basic Energy Sciences, under Award # ER 46640-SC0002567 (de-sc0006671). A portion of this work was performed at the National High Magnetic Field Laboratory, which is supported by National Science Foundation Cooperative Agreement No. DMR-1157490 and the State of Florida.

*Current address: QuTech and Kavli Institute of Nanoscience, Delft Technical University, 2600 GA Delft, The Netherlands.

-
- [1] A. A. Koulakov, M. M. Fogler, and B. I. Shklovskii, Phys. Rev. Lett. **76**, 499 (1996).
 - [2] M. M. Fogler, A. A. Koulakov, and B. I. Shklovskii, Phys. Rev. B **54**, 1853 (1996).
 - [3] M. P. Lilly, K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **82**, 394 (1999).
 - [4] R. R. Du, D. C. Tsui, H. L. Stormer, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Solid State Commun. **109**, 389 (1999).
 - [5] M. P. Lilly, K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **83**, 824 (1999).
 - [6] W. Pan, R. R. Du, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Phys. Rev. Lett. **83**, 820 (1999).
 - [7] K. B. Cooper, M. P. Lilly, J. P. Eisenstein, T. Jungwirth, L. N. Pfeiffer, and K. W. West, Solid State Commun. **119**, 89 (2001).
 - [8] J. Zhu, W. Pan, H. L. Stormer, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **88**, 116803 (2002).
 - [9] K. B. Cooper, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **92**, 026806 (2004).
 - [10] G. Sambandamurthy, R. M. Lewis, H. Zhu, Y. P. Chen, L. W. Engel, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **100**, 256801 (2008).
 - [11] H. Zhu, G. Sambandamurthy, L. W. Engel, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **102**, 136804 (2009).
 - [12] I. V. Kukushkin, V. Umansky, K. von Klitzing, and J. H. Smet, Phys. Rev. Lett. **106**, 206804 (2011).
 - [13] S. P. Koduvayur, Y. Lyanda-Geller, S. Khlebnikov, G. Csathy, M. J. Manfra, L. N. Pfeiffer, K. W. West, and L. P. Rokhinson, Phys. Rev. Lett. **106**, 016804 (2011).
 - [14] Y. Liu, D. Kamburov, M. Shayegan, L. N. Pfeiffer, K. W. West, and K. W. Baldwin, Phys. Rev. B **87**, 075314 (2013).
 - [15] Y. Liu, S. Hasdemir, M. Shayegan, L. N. Pfeiffer, K. W. West, and K. W. Baldwin, Phys. Rev. B **88**, 035307 (2013).
 - [16] B. Friess, V. Umansky, L. Tiemann, K. von Klitzing, and J. H. Smet, Phys. Rev. Lett. **113**, 076803 (2014).
 - [17] N. Samkharadze, K. A. Schreiber, G. C. Gardner, M. J. Manfra, E. Fradkin, and G. A. Csathy, Nat. Phys. **12**, 191 (2016).
 - [18] Q. Shi, S. A. Studenikin, M. A. Zudov, K. W. Baldwin, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **93**, 121305 (2016).
 - [19] Q. Shi, M. A. Zudov, J. D. Watson, G. C. Gardner, and M. J. Manfra, Phys. Rev. B **93**, 121411 (2016).
 - [20] J. Pollanen, K. B. Cooper, S. Brandsen, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **92**, 115410 (2015).
 - [21] M. A. Mueed, M. S. Hossain, L. N. Pfeiffer, K. W. West, K. W. Baldwin, and M. Shayegan, Phys. Rev. Lett. **117**, 076803 (2016).
 - [22] I. Sodemann and A. H. MacDonald, arXiv:1307.5489 (2013).
 - [23] T. Jungwirth, A. H. MacDonald, L. Smrčka, and S. M. Girvin, Phys. Rev. B **60**, 15574 (1999).
 - [24] T. D. Stanescu, I. Martin, and P. Phillips, Phys. Rev. Lett. **84**, 1288 (2000).
 - [25] We limit our discussion to single-subband 2DEG.
 - [26] Even early experiments [5] have shown that B_{\parallel} applied perpendicular to the native stripes can reduce or even eliminate the anisotropy at $\nu = 9/2$ and $\nu = 13/2$, in contrast to theoretical predictions [23, 24].
 - [27] J. D. Watson, G. A. Csáthy, and M. J. Manfra, Phys. Rev. Applied **3**, 064004 (2015).
 - [28] We limit the range of B_y to avoid complications from LL-mixing effects.
 - [29] At $B_{\parallel} = 0$, $E_N = E$ and $E_A = 0$.
 - [30] In our sample Δ decreases by about 15% over the density range studied [27].
 - [31] $\nu = 9/2$ and $11/2$ are characterized by the same 2D wavefunction, stripe period, and inter-LL spacing, justifying their direct comparison in Fig. 2.
 - [32] At a fixed ν , larger n_e also translates to a reduced stripe period which can also affect E_N . However, Ref. 8 found that E_N vanishes at both $\nu = 9/2$ and $11/2$ at the same n_e , indicating that this effect is of minor importance.
 - [33] I. L. Aleiner and L. I. Glazman, Phys. Rev. B **52**, 11296 (1995).
 - [34] I. V. Kukushkin, S. V. Meshkov, and V. B. Timofeev, Phys. Usp. **31**, 511 (1988).
 - [35] Screening at a wavevector of stripe modulation is characterized by $\varepsilon(1 + a/\pi a_B)$, where $\varepsilon \approx 12.8$ is the dielectric constant of GaAs, $a \approx 2.8R_c$ is the stripe period, R_c is

the cyclotron radius, and $a_B \approx 10$ nm is the Bohr radius [1, 33, 34].

- [36] At $\hbar\omega_c/\Delta > 0.5$ theory [23] predicts $E_A < 0$ and stripes parallel to B_{\parallel} emerge when the lowest LL of the second subband is depopulated by B_{\parallel} [37]. However, further increase of B_{\parallel} ultimately leads to perpendicular stripe

alignment in this regime [23, 37].

- [37] W. Pan, T. Jungwirth, H. L. Stormer, D. C. Tsui, A. H. MacDonald, S. M. Girvin, L. Smrčka, L. N. Pfeiffer, K. W. Baldwin, and K. W. West, Phys. Rev. Lett. **85**, 3257 (2000).